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Review

Personal respiratory protection and resiliency in a pandemic, the evolving disposable versus reusable debate and its effect on waste generation

Andrea Hicks^{*}, Sila Temizel-Sekeryan, Wissam Kontar, Ramin Ghamkhar, Mónica Rodríguez Morris

University of Wisconsin-Madison, Department of Civil and Environmental Engineering, United States



ABSTRACT

The COVID-19 pandemic sweeping much of the globe is not anticipated to be short in duration, with contingency plans suggesting that it may last at least eighteen months. In the United States, one of the critical issues in coping with the pandemic has been a lack of essential personal protective equipment (PPE), at the local, state, and national level. As COVID-19 is primarily transferred through respiratory routes, adequate respiratory protection is a dire necessity. The shift from durable and reusable medical supplies in recent years to their single use counterparts has reduced the resiliency of the medical system with respect to PPE and other critical supplies in the current pandemic. This work explores the role of reusable compared to single use respiratory protection in the current pandemic, including reprocessing of single use options, from the perspective of number of equivalent protection devices needed. The current state of literature is also reviewed to provide context to this work, with respect to resource procurement. The economic cost of PPE throughout a pandemic is explored, and it is found that utilizing reusable PPE options depending on filter cycling may be less costly. Increased waste production is another issue with the current pandemic, and this is explored utilizing a mass basis, finding that reusable respiratory PPE would generate less waste than using single use PPE in a business as usual scenario. As future outbreaks of COVID-19 are likely along with other future pandemics, this work provides insights at how to prepare from the standpoint of PPE, and in particular respiratory protection.

1.0. Introduction

The debate surrounding reusable versus disposable medical equipment, has often centered around three primary considerations: (1) the potential for reusable equipment to serve as a vector of transmission for pathogens, (2) the comparative economic cost of disposable versus reusable equipment, and (3) finally the comparative environmental impact of the disposable versus reusable options (Campion et al., 2015; Eckelman et al., 2012; Hicks et al., 2016; Sherman and Hopf, 2018; Siu et al., 2017; Sreijic, 2016; Thiel and Horwitz, 2019; Tvede et al., 2012; Unger and Landis, 2014; Vozzola et al., 2018; Yung et al., 2010). At times the conversation has also included other aspects, such as the comfort of reusable versus disposable options. What has not been part of the debate until recently, is the change in the resiliency of the healthcare system, when the majority of stocks of a necessary piece of equipment are intended for a single use and therefore considered disposable, particularly in the case of a pandemic, when demand surges.

The current COVID-19 pandemic is challenging the medical system in the United States in a myriad of ways. One of the most popularized issues has been a lack of personal protective equipment (PPE) for medical staff, specifically during the first few months of the outbreak – although this issue is still pervasive (The Lancet, 2020). This has included items such as hand sanitizer, face shields, gowns, gloves, and

respiratory protection (FDA, 2020a; Ranney et al., 2020). Which has resulted in the need to reuse and clean what were intended to be single use items, because there simply are not enough available (3 M, 2020). Different methods are currently being tested and deployed in the context of the pandemic to clean these items while maintaining desirable efficacy, so that they are able to be reused. While this may be the most realistic option in the current situation, it is necessary to consider the need for reusable medical supplies and their potential to be cycled more quickly, when demand spikes, such as in a pandemic situation. The authors also note that the current intent for some of the reprocessing of single use medical items is only intended in pandemic situations, such as N95 single use respirators (referred to as N95s for the rest of the work). N95s, their alternatives, and reprocessing options will be the focus of this work, and this has emerged as a critical issue with response to the current pandemic. In this work we present a review of the current literature and model the potential for N95 masks to be substituted with reusable options. The authors also acknowledge that the best guidance on the COVID-19 pandemic is changing on a daily basis and the sources included here reflect the current state of knowledge at the time of submission (October 31, 2020). This work seeks to (1) provide a critically needed literature review as to the state of PPE usage and alternatives in the current pandemic, (2) utilize the issue of respiratory protection to illustrate how the current pandemic has changed the disposable versus

^{*} Corresponding author.

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reusable debate within health care, (3) illustrate these issues with positing scenarios from an economic and environmental perspective, and (4) provide guidance given the current state of affairs. Fig. 1 summarizes the scope and organization of this work.

1.1. Duration of the pandemic

The COVID-19 pandemic has affected everyday life in an unprecedented manner in recent history (Boccaletti et al., 2020). The 1918 Spanish Flu is often considered the closest analogue to the current situation, which killed around 50 million people over 100 years ago (CDC, 2017a). The current pandemic is even more challenging to contain due to the increased global connectivity of the world today, compared to 100 years ago (Cirillo and Taleb, 2020). As of October 28, 2020 the COVID-19 pandemic has reached over 44 million global confirmed cases with over 1.1 million confirmed deaths (The New York Times, 2020). It is anticipated that the COVID-19 pandemic will not be over quickly, as the US Virus plan assumes that the pandemic will last 18 months (Baker and Sullivan, 2020; HHS, 2020). This means that although acute waves of infection may be found in early hotspots, such as Washington and New York (Axelson, 2020; Savransky, 2020; The Lancet, 2020), COVID-19 and the demand for PPE will not end quickly. It has also been suggested that, like other diseases (e.g. polio and measles), there is a potential for COVID-19 to flare annually (Cohen, 2020).

1.2. Why respiratory protection is important in the COVID-19 pandemic

Although the science around COVID-19 transmission is currently evolving, there is evidence to suggest that transmission of the virus occurs chiefly through the air (Allen and Marr, 2020; Dancer et al., 2020; WHO, 2020). Current experimental work has found that it can persist in aerosols for up to 16 h, which is an unusually long amount of time for similar viruses (Fears et al., 2020). A recent modeling study of aerosol transmission in a poorly ventilated restaurant in China, supports

the theory that this is a vector of concern (Li et al., 2020). The potential for infection through inhalation has made appropriate respiratory PPE a critical issue in this current pandemic.

N95s have emerged as one of the critical PPE components for respiratory protection in the COVID-19 response, due to the role of airborne transmission of the virus. These respirators are 95% efficient for particles and are equivalent to a MERV 16 (minimum efficiency reporting value) filter. This means that N95s will reduce the flow of particles larger than 0.3 micrometer (μm) by 95% (Livingston et al., 2020). A major issue is that these N95s are designed to be single use, which is a challenge from a sourcing perspective due to the surge in demand for these supplies. This has changed how hospitals and medical systems are using these supplies, with respect to deviations from normal protocols, which have been allowed to occur during the current pandemic. Months into the pandemic in the US, there are still shortages of these single use intended respirators (Garrett, 2020; Jacobs, 2020; Wan, 2020), particularly as other medical services which closed in the early stages of the pandemic are attempting to reopen, such as dental offices. The dire shortage of necessary respiratory protection for the COVID-19 pandemic has led to the usage of PPE in ways that it was not originally intended. In Section 1.3 the typical usage and relative advantages and disadvantages of respiratory PPE are explored, while in Section 1.4 the different reprocessing strategies for N95s is explored based on the current literature related to the pandemic.

1.3. Typical respirator lifetimes and options

Typically, medical N95s which are approved by National Institute for Occupational Safety and Health (NIOSH), are recommended for healthcare personnel (HCP) in order to control airborne infection exposures resulting from small particle aerosols (CDC, 2020a, 2018). According to the recent literature review conducted by Bartoszko et al. (2020), surgical/medical masks provide similar levels of protection as N95 respirators for non-aerosol generating procedures, influenza and

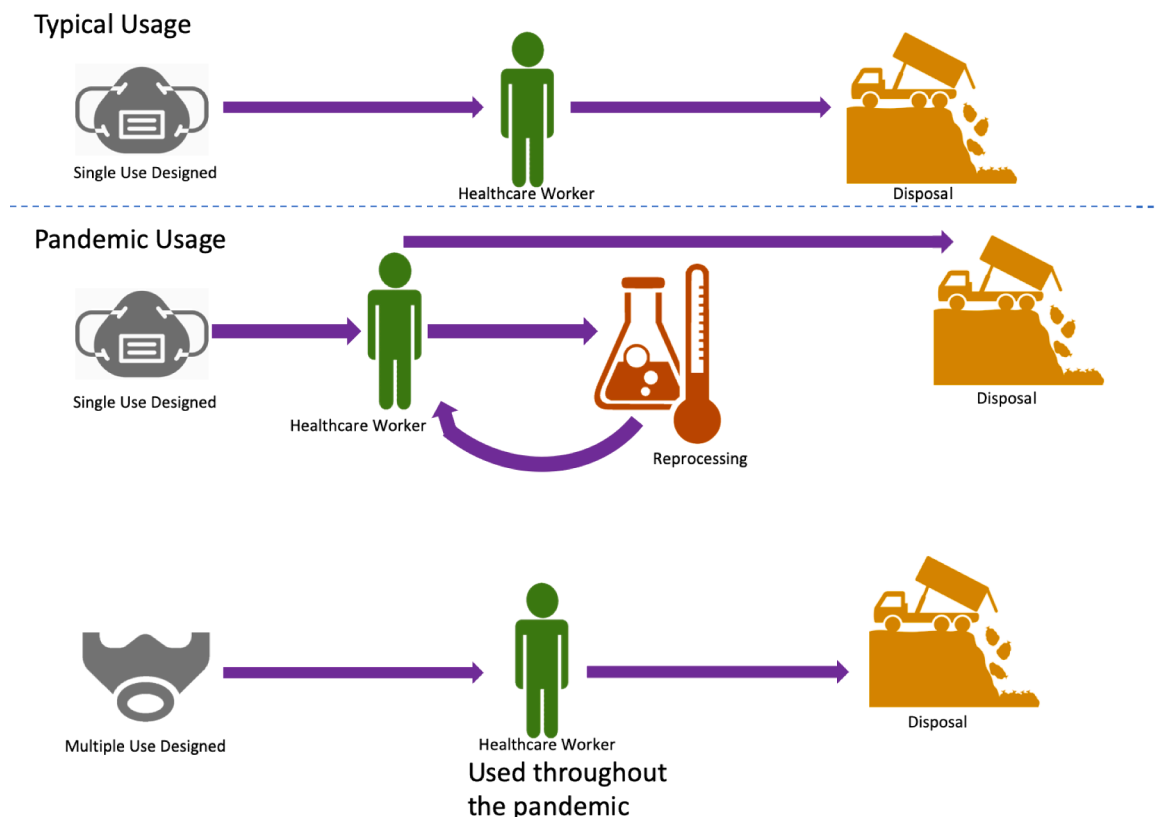


Fig. 1. Difference in life cycle usage scenarios of respiratory protection during non-pandemic and pandemic times.

viral respiratory infections. The efficacy of surgical/medical masks on COVID-19 is still subject to debate as there are not yet any published studies addressing this issue (Greenhalgh et al., 2020). However, recommendations are in place that, in order to save N95 respirators and their alternatives for those who are in close contact with patients having COVID-19, surgical/medical masks may be used (Bartoszko et al., 2020; CDC, 2020b).

Due to the limited supply of disposable N95 respirators during current pandemic, new guidelines were issued by the Centers for Disease Control and Prevention (CDC) and US Food and Drug Administration (FDA). The CDC provided a guidance on the extended use and/or limited reuse of N95 respirators in accordance with certain practices (CDC, 2020c). Similarly, FDA issued additional guidelines to authorize the use of alternative equipment (Hinton, 2020). Table 1 summarizes the authorized list of particulate-filtering air purifying respirators. These include non-powered air-purifying particulate filtering facepiece respirators (FFR), elastomeric half and full facepiece respirators, powered air purifying respirators (PAPR), FFRs that are expired but have been stored under recommended storage conditions and FFRs that are decontaminated properly (Hinton, 2020). Moreover, in order to increase the availability of PPE supplies, the FDA issued an Emergency Use Authorization (EUA) and permitted the use of additional classes of FFRs including NIOSH-approved air purifying respirators, imported and non-NIOSH-approved disposable FFRs, and non-NIOSH-approved disposable FFRs manufactured in China (FDA, 2020b). With respect to the use of expired FFRs, although some manufacturers established a shelf life for their products (ranging from 3 to 9 years), a researcher argued that FFRs do not typically expire in terms of their functionality, but may be physically damaged over time (Landsverk, 2020). Likewise, NIOSH conducted a research to evaluate the performances of stockpiled and expired air purifying respirators, particularly N95s, and concluded that 98% of them functioned in accordance with the NIOSH standards (Greenawald et al., 2020). It should be noted that NIOSH does not approve the N95s that are past their manufacturer-designated shelf life; however, CDC/NIOSH authorized their use during increased demand and decreased supply (CDC, 2020a; Greenawald et al., 2020).

Although FFRs are not designed for reuse, there may be exceptions during airborne disease outbreaks ([CDC, 2020c](#); [ECRI, 2020](#)). There is no strict restriction on the number of uses, but to maintain the suggested fit factor and ensure an adequate safety margin, research suggested that FFRs may be reused no more than five consecutive times (i.e. before they become unfunctional) if no additional manufacturer guidance is available ([Bergman et al., 2012](#); [Viscusi et al., 2011](#)). In the published guidelines and literature, there are three different considerations for reusing N95 respirators, which is often referred to as “limited reuse”. One option is reusing N95s for multiple encounters with patients (i.e. putting them on but removing after each use) under strict procedures for handling, labeling and storing ([CDC, 2020c](#)). This option requires removing the respirator after each use, hanging in a designated area or storing in a breathable container to prevent cross-contamination and labeling it with the name of the user. It should be noted that, according to the limited reuse guidelines, N95 should be discarded if they are physically damaged or contaminated with bodily fluids ([CDC, 2020c](#)). Another option is the repeated use of N95 for a certain period of time ([CDC, 2020d](#)). In this option, five respirators are issued to a single health care provider. One respirator is used per day and stored after each work shift for a duration of five days without going through any decontamination process. This way each personnel would have five FFRs and use them for an extended period of time. It should be noted that, a special care should be given to allowing at least 72 h to elapse between using the same respirator ([CDC, 2020d](#)). The third option is reusing N95 respirators after a proper decontamination process (e.g. using steam, disinfectants, ultraviolet germicidal irradiation etc.). Since the materials vary in each respirator model, the guidance on the decontamination method should be provided by the manufacturers or third parties ([ECRI, 2020](#); [FDA, 2020b](#)). Another approach that may be practiced during FFR shortage is

Table 1

Authorized list of particulate-filtering air purifying respirators for COVID-19 pandemic.

Class	Models	Are they designed for reuse?	Number of possible reuse	Sources
Filtering facepiece respirators (FFR)	Standard N95s (NIOSH-approved) Surgical/medical N95s (NIOSH-approved and FDA cleared) N99, N100, P95, P99, P100, R95, R99, R100 (NIOSH-approved) NIOSH-approved air purifying respirators Imported, Non-NIOSH-approved disposable FFRs Non-NIOSH-approved disposable FFRs manufactured in China FFRs that are decontaminated properly FFRs that are expired but have been stored under recommended storage conditions	No (CDC, 2019, 2017b), but there may be exceptions during increased demand	If manufacturer guidance is not available, maximum of five consecutive uses is recommended (Bergman et al., 2012; Viscusi et al., 2011)	(CDC, 2020a) (CDC, 2020a) (CDC, 2020a) (CDC, 2020a; FDA, 2020b) (CDC, 2020a; FDA, 2020b) (CDC, 2020a; FDA, 2020b) (Hinton, 2020) (Hinton, 2020)
Elastomeric half-mask air purifying respirators	N95, N99, N100, P95, P100, R95, R99, R100	Yes (reusable facepiece and replaceable cartridges or filters) (CDC, 2017b)	N/A (repeated disinfection and cleaning does not affect the durability of these respirators) (Radonovich, 2017)	(CDC, 2020a, 2018)
Elastomeric full facepiece air purifying respirators	N95, N99, N100, P95, P100, R95, R100	Yes, (reusable facepiece and replaceable canisters, cartridges, or filters) (CDC, 2017b)		(CDC, 2020a, 2018)
Powered air purifying respirators (PAPRs)	HEPA PAPR with full facepiece, with half-mask facepiece, with helmet, with hood, or with hood and helmet	Yes (reusable components and replaceable filters or cartridges) (CDC, 2017b)		(CDC, 2020a, 2018)

HEPA: High-Efficiency Particulate Air; FDA: Food and Drug Administration; NIOSH: The National Institute for Occupational Safety and Health.

referred to an “extended use”, which is wearing the same respirator without removing it between patients who have the same infection. In this approach, one FFR should be worn by the same HCP for no more than 8–12 h, and after the shift, the FFR should be discarded properly (i. e. should not be reused) (CDC, 2020b). As included in Table 1, besides FFRs, the use of elastomeric half-mask and full facepiece air purifying respirators and PAPRs is authorized for the current pandemic. Different from FFRs, these are designed for reuse after cleaned/disinfected between each patient interaction (CDC, 2019). A summary discussing the advantages and disadvantages of different classes of respirators is provided in Table 2.

As discussed previously, some exceptions for the authorized

Table 2

Summarized advantages and disadvantages of air purifying respirators (compiled from (Clever et al., 2018; Radonovich, 2017; Rebmann, 2009)).

Class	Advantages	Disadvantages
Filtering facepiece respirators (FFR)	<ul style="list-style-type: none"> - Ideally single-use, do not require additional disinfection or maintenance process - Inexpensive (approx. \$0.75, reached about \$6.00 during the pandemic) - Provide filtering during inhalation and exhalation 	<ul style="list-style-type: none"> - Fit testing is required - Discarded after use
Elastomeric (half-mask or full facepiece) air purifying respirators	<ul style="list-style-type: none"> - Reusable - Durable to repeated cleaning and disinfection processes - Respirator does not have an expiration date - Relatively inexpensive (approx. \$30 including \$10 for the cartridges) - Available for routine use and stockpiling - Half-mask covers nose and mouth - Full facepiece provides face/eye protection 	<ul style="list-style-type: none"> - Fit testing is required - Require cleaning and disinfection process according to the manufacturer's instructions after each use - Cartridges have expiration dates. - Approx.\$10 cartridge needs to be exchanged - Require proper storage between work shifts - Hard to communicate with patients
Powered air purifying respirators (PAPRs)	<ul style="list-style-type: none"> - Reusable - Durable to repeated cleaning and disinfection process - More effective than N95 respirators - Fit testing is not required - Provide face/eye protection 	<ul style="list-style-type: none"> - Expensive (about \$800) - Do not provide filtering during exhalation - Equipped with battery-powered blower which needs to be recharged and maintained - Have disposable head covers - Require cleaning and disinfection process according to the manufacturer's instructions after each use - Require proper storage between work shifts - Hard to communicate with patients

particulate-filtering air purifying respirators (e.g. limited reuse, extended use, using expired respirators etc.) have been made during the current outbreak, as there have been shortages of PPE especially for HCPs. Official guidelines, in both national (e.g. CDC, FDA) and international (e.g. WHO) levels, on facemasks, respirators and other PPEs are being updated on a regular basis.

In summary, the dependence of the medical system on single use respirators has created a bottleneck when demand surges, such as is occurring during the current pandemic. There are various advantages and disadvantages to the employment of single usage PPE compared to multiuse PPE among HCP. One major advantage of multiuse PPE is that it is designed for reuse, and that reuse has the potential to be extended and serve to buffer increases in demand.

1.4. Reprocessing methods

Reprocessing methods are being applied to N95s in order to extend their useable lifetime. In general for PPE processing to be successful it should incorporate at least three aspects: (1) provide acceptable efficacy in terms of microorganism load reduction (targeted contaminant), (2) maintain the applicability of equipment to be reused after reprocessing by retaining fitting and filtration performance, and (3) prevent the unintended consequences (e.g. user exposure to a carcinogenic chemical) (ECRI, 2020; Lore et al., 2012; Rutala et al., 2017; Traverso et al., 2020;

Viscusi et al., 2011; Ghamkhar, 2018).

Based on the state-of-the-art disinfection methods that are currently being used for medical equipment, the CDC has suggested eight techniques as potential disinfection methods for FFRs, including N95s. These methods can be grouped as are radiation-based, heat-based, and chemical-based. A summary of the methods, treatment techniques, efficacies, use cycles (tested), and targeted equipment are compiled from the literature, tabulated in Table 3, and further discussed in the SI.

So far, there is not a single reprocessing method which has been determined to be superior to all of the other methods. A major reason is the tradeoff between decontamination and damage of the N95s. This raises the question as to what level of damage to the N95 is acceptable during cleaning. The CDC has suggested that UVGI, MHI, and VHP are the most promising methods for FFR decontamination (CDC, 2020d). However, Bergman et al. showed a significant filter penetration (exceeds 5%) after 3 consecutive VHP treatment (Bergman et al., 2010). Therefore, UVGI for UV-resistant equipment and MHI for heat-resistant equipment could be suggested as applicable methods for treatments (up to three) based on the existing performance results.

In summary, FFRs reprocessing is one potential option to increase health system resiliency when supplies become depleted during a pandemic or airborne disease outbreak. The production of FFRs, that are compatible to be reprocessed by at least one practically feasible treatment technique (Table 3) while maintaining acceptable performance and fit under several treatment cycles, could significantly help to buffer the supply-demand balance during a demand surge. Future research could focus on the optimal FFR material and disinfection methodology to achieve an elevated supply conservation and resilience. One significant issue, however, is the availability of reprocessing options, which is not accessible in all places. Another is the cost to perform the reprocessing, which data is currently sparse and variable on. Although if price gouging is occurring for both the single and multiple use designed options, then if available the reprocessing may be more attractive financially as well.

1.5. Changing use patterns

Use patterns and protocols associated with respiratory PPE have changed as a result of the pandemic. For example, in many health systems, employees and visitors are required to wear (and are often provided with) surgical masks when entering a building (Fox, 2020). This is not a typical practice in the US during normal times. At the same time, these surgical masks are being worn for a much longer duration than is typical, where usually PPE is discarded after each patient encounter (CDC, 2020e). The same is true for N95s. Respirators are not routinely utilized in hospitals and are usually used when there is a high-risk situation (respiratory risk patients) that necessitates respiratory protection (Chughtai et al., 2020). Essentially, previous consumption of these N95 were relatively very low. The frequency with which the N95 masks are discarded has changed significantly, compared to normal times (CDC, 2020e). Typically, N95s are considered disposable, and discarded after each patient contact (CDC, 2020c). Early in the pandemic, hospitals also canceled elective procedures and converted other wards into COVID-19 wards, which effected the consumption of PPE (Neighmond, 2020; Paavola, 2020). Current popular media reports suggest that due to the sometimes dire shortages of N95s, that other patterns of extended usage are occurring. These changes in usage patterns are critical to consider understanding the shifts in resiliency of the US medical system with respect to the current pandemic, and a marked increase in the consumption and use of respiratory protection.

1.6. The case for reusable respiratory protection

The case has been made for reusable respiratory protection in order to prepare for pandemics before. Prior to the current pandemic, influenza has been the primary concern, and in 2006 the Institute of Medicine

Table 3
Personal Protective Equipment (PPE) Treatment Techniques and their Associated Characteristics.

Method	Treatment Technique	Efficacy	Use Cycles (tested)	Target Equipment	Reference
Ionizing radiation (e.g. Gamma, X-ray, E-beam)	Radiation	4 log10 reduction of single-stranded RNA viruses radiation dose of 5–10 kgGray	1 N/R*	FFR ^s Non-respiratory PPEs	(3M, 2020; Cramer et al., 2020) (GIPA and IIA, 2017)
Ethylene Oxide (EtO)	Chemical	6 log10 reduction of bacterial inoculum	4 4	FFRs Non-respiratory PPEs	(CDC, 2020d; Kumar et al., 2020; Rutala et al., 2020; Rutala and Weber, 2016) (Alfa et al., 1996; Bergman et al., 2010; Sreejith and Sasi, 2020)
Ultraviolet Germicidal Irradiation (UVGI)	Radiation	>4 log10 reduction of H5N1 virus	4 N/R*	FFRs Non-respiratory PPEs	(3M, 2020; CDC, 2020d; Lore et al., 2012) (Castellanos et al., 2020)
Microwave Generated Steam (MGS)	Heat + Radiation		21 N/R*	FFRs Non-respiratory PPEs	(3M, 2020; CDC, 2020d; Lore et al., 2012) (Varma, 2005)
Moist Heat Incubation (MHI)	Heat		4 N/R*	FFRs Non-respiratory PPEs	(3M, 2020; CDC, 2020d; Lore et al., 2012) (Boca et al., 2002)
Hydrogen Peroxide Gas Plasma (or Vaporous Hydrogen Peroxide, VHP)	Chemical	6 log10 reduction in organism viability	3 21	FFRs Non-respiratory PPEs	(Bergman et al., 2010; FDA, 2020d) (Richter, 2020)
Liquid hydrogen peroxide (LHP)	Chemical	>5 log10 reduction of virucidal activity	4 N/R*	FFRs Non-respiratory PPEs	(Bergman et al., 2010) (CDC, 2020d; Sattar et al., 2002)
Microwave Steam Bags (MSB)	Heat + Radiation	>3 log10 reduction of MS2 bacteriophage	4	FFRs	(Fisher et al., 2011; Schöpe and Klopotek, 2020)

* N/R: Not Reported.

warned that, during a six week pandemic, at least 90 million N95 respirators would be needed for medical personnel (Institute of Medicine, 2006). They also cautioned, “In the event of an extended pandemic, there will be the inevitable increasing demand by the public for masks, which cannot be met by the current, or even ramped-up U.S. production of disposable masks.” In the same report it was suggested that the world was overdue for a pandemic event, and it was just a matter of time until one occurred, so it was critical to think about preparedness. Although they found that single use respirators could be reused, they stressed that it should only be done when there was not an adequate supply, and that it would be better to stockpile reusable respirators instead of single use items. This report was utilized as part of the effort by the United States federal government to procure machine capacity which would be able to greatly increase the disposable N95 mask making capacity of the country, however, as reported previously that has not yet come to fruition (Swaine, 2020). The 14 year old report essentially predicted the shortages of PPE seen due to the current pandemic as a function of the US’s reliance on single use PPE, and warned that reusable PPE should be stockpiled for usage, in order to increase the resiliency of the medical system.

Reusable respiratory protection, such as the elastomeric air purifying respirators are designed for multiple usages and could be instrumental in increasing the buffering capacity of the medical system to PPE shortages in the case of increased demand, such as a pandemic (Clever et al., 2018; Radonovich, 2017; Rebmann, 2009). Although these respirators do require cartridges, replacement frequency of these cartridges is fairly low. One leading manufacturer suggests that cartridge replacement should occur if (1) it becomes difficult to breath comfortably, or (2) the filter becomes dirty or physical damage occurs (3 M, 2014). This suggests that due to the relatively low level of particulate matter in air, that

these cartridges could last for a significant duration of a pandemic. Chughtai et al. (2020) found that reusable FFR would likely be preferable in a pandemic situation compared to N95 options.

This work, will posit different scenarios as to the consumption of single use N95s during the current COVID-19 pandemic (including reprocessing and other extended usage measures), compared to reusable respirators to understand the potential form replacement and decreased supply demand. The economic cost of different scenarios will be quantified to provide context to this literature review. The mass of waste generated for disposal through the usage of the same scenarios will also be presented as a comparative metric. These scenarios are meant to provide context to the literature reviews, and not as absolutes. We recognize that due to the current data gaps and uncertainties that they may not be entirely representative.

2. Methods

The United States Virus plan is operating under the assumption that the pandemic could last 18 months (Baker and Sullivan, 2020; HHS, 2020). It is not yet known whether this is an accurate prediction, however, it will be utilized as the starting point for this work. Multiple scenarios will be explored, as shown in Table 4, to examine the potential to shift consumption of different respiratory protection options.

For the Business as Usual (BAU) scenario, it is assumed that with each new patient encounter the medical personnel would utilize a new N95. In normal times, used N95s would be removed and discarded after each patient encounter (CDC, 2020e). Thus, it is necessary to estimate how many patients a medical professional would see during a shift. For this work, emergency room physicians will be the focus of the study, as they are easier to track than other personnel are. However, all medical

Table 4
Scenarios considered in the modeling.

Scenario	Consumption
Business as Usual (BAU)	120 disposable N95s per week
Single Person Damage (SPD)	1 disposable N95 per week
Single Person Rotate (SPR)	5 disposable N95s every 5 weeks
Reuse After Decontamination (RAD)	2 disposable N95s per week + 3 reprocessed N95s
Reusable Respirator Cartridge Monthly (RRCM)	1 reusable respirator for duration, 2 new cartridges every 1 month
Reusable Respirator Cartridge Weekly (RRCW)	1 reusable respirator for duration, 2 new cartridges every 1 week

personnel are critical in a pandemic, and the use of physicians in tracking is not meant to suggest that one group is more important than another when it comes to patient care or resource consumption. In addition, tracking emergency room physicians could be a representation of worst case scenario (maximum patient encounter) during a pandemic, when patients hospitalization surges. Emergency room physicians have been found to see between 1.5–3.13 patients per hour (Jensen, 2015). The value of 2 patients per hour will be utilized in this work, while also assuming a 12 hour shift, which brings the total to 24 patients per shift. Assuming that the medical provider wore a new N95 per patient (which is a normal use rate in non-pandemic times, however, not a normal number of patients that would be suspected to have an issue which would require N95 usage), that would equate to 24 N95s per shift. Based on a survey by the American Medical Association, most doctors (36%) work between 40 and 50 h per week, while 26% work between 51 and 60 h per week (American Medical Association, 2015). Due to the pandemic conditions, the value of 60 h per week, or five 12 hour shifts will be utilized in this analysis. Which would equate to 120 N95 respirators used per week. The authors recognize that this is simply not occurring currently due to a lack of respiratory protection supplies, however, it will serve as the BAU scenario for this work.

In the Single Person Damage (SPD) scenario it is assumed that the health care provider is assigned a new N95 respirator weekly and wears it until it is damaged. We are assuming that the N95 will be damaged after continuous usage during a week. It is also recognized that in the current pandemic that medical personnel are taking measures to increase the lifetime of PPE, by doing things such as storing them in labeled paper bags overnight or wearing a clothin mask over them (CDC, 2020d).

Under the Single Person Rotate (SPR) scenario, each person is assigned 5 N95 respirators, which they rotate daily, and store in between uses. Assuming similar to the SPD scenario that the respirator would be good for 1 week of continuous usage, then after 25 weeks of usage, the person would need 5 new N95 respirators.

The Reuse After Decontamination (RAD) is a scenario which has been receiving attention recently (Bergman et al., 2010; FDA, 2020d; Nazeeri et al., 2020). For this case it will be assumed that a N95 is worn for a single shift, and then collected for decontamination. After it is decontaminated, it would then be put back into the general pool for reuse. One potential variability in this approach is the number of times that is recommended for N95s to be reprocessed, and it ranges between 1 and 21 usage cycles (Table 4). Meaning that at the worst a single N95 could be used once additionally, whereas at the best it could be used 21 times, and also potentially by 21 different people. Although how N95s are redistributed after reprocessing varies from healthcare setting to healthcare setting, with some providers receiving their own previously worn N95s back and in other places receiving ones from the overall pool. There is also the issue of damaged N95s to consider with respect to reprocessing. The current guidelines suggest that any N95 which is damaged or dirty (which includes makeup residue) should be discarded. The rates have been suggested to be between 30 and 50% of N95s sent for reprocessing, which would be expected to increase as N95s are reprocessed subsequent times. For this work, we will use the most

commonly suggested lifetime of 4 usages (3 treatment cycles in between). Which would equate to 1.25 new N95s per week, over 5 shifts. In order to incorporate this into the analysis, an equivalence of 2 new N95s per week will be utilized for this scenario.

Finally, in the Reusable Respirator Cartridge (RRC) scenarios (RRCM and RRCW), it will be assumed that each medical provider is assigned a reusable respirator for the duration of the pandemic event. The guidance as to when to change the filtering cartridge is complex, and are situated around contaminants other than viruses (3 M, 2014). For this work it will be assumed that the respirator itself would last the entire duration of the pandemic, while the cartridges would be changed out every 1 month (RRCM), meaning that 36 cartridges would be needed for the duration of the event as 2 are utilized at once in most models (3 M, 2014). Or RRCW where the cartridges are changed out each week. The current guidance as to when to change these cartridges revolves around ease of breathing through the cartridges, however, these guidelines were conceived for dusty environments, which healthcare facilities are not. It likely that using those guidelines it would not be necessary to change cartridges at all during the current pandemic. Which suggests that in the future it would be beneficial to develop new guidelines relative to virus transmission. Anecdotally, in discussion with medical personnel, the guidelines as to when to change out cartridges varies significantly, from a little as every 2 weeks to as long as perpetuity for the pandemic, and only being changed when it is difficult to breathe through the respirator. Cartridges exist both for particulates and for more advanced volatile contaminants. Although the particulate cartridges are sufficient from a filtration perspective, the ones that also remove volatiles are somewhat preferred as they have a hard casing which is easier to wipe down and clean between uses. In this work, we are modeling the particulate-only cartridges as they are more comparable to the N95 disposable respirators.

There are also economic costs to the consumption, which the usage of reusable respiratory protection also has the potential to buffer against. During typical time a single usage N95 masks costs around \$0.75 (Clever et al., 2018; Radonovich, 2017; Rebmann, 2009), however, it has been reported that the price has skyrocketed due to demand to price as high as \$6 (Reuters, 2020). Reusable respirators typically cost around \$30 (Clever et al., 2018; Radonovich, 2017; Rebmann, 2009), with replacement filters for particulates between \$5 and \$10 per package of two. We will use a cost of \$7 per package and assume the respirator does not come with an initial set. The costs for reprocessing single use N95s have understandably not be a focus in the current situation. However, it is still relevant to consider, typically reprocessed medical equipment is around half the price of new equipment (Lagasse, 2019), as no such data currently exists for N95 reprocessing to the knowledge of the authors, we will assume of cost of \$0.35 per reprocessed N95, following the rule of thumb that reprocessed medical device is worth approximately 40–60% of the virgin medical device (Practice Greenhealth, 2011). At this time, no publicly data available data exists for the costs of either external nor internal reprocessing, which is another limitation of this work.

Although economic considerations are a more pressing concern in the current pandemic, there are also issues to consider with respect to waste generation and the implications of the pandemic on the sustainability of the healthcare field (UCL Plastic Waste Innovation Hub, 2020). The N95 respirator has a mass of 9.2 gs (+/- 1 0.31 g). This was determined by weighing 16 samples of one style of N95. The elastomeric respirator had a mass of 79.5 g. Two used filters (one for each side of the respiratory) of the hard shelled variety with a filter inside were massed, and found to have masses of 36.1 g and 36.4 g. We will use a mass of 36.3 g for the course of this analysis. These filters had been utilized previously for sanding and were full of particulate matter. Much like well-used filter may be by the end of its life. The authors take into account the mass of the elastomeric respirator itself, with it being disposed of in during the final week of the scenarios. The authors would have liked to be able to include a greater variety of mass data, however, due to

scarcity issues of PPE during the current pandemic, that was not possible, which is another limitation of this work.

3. Results

The potential exists to reduce the demand for single use N95 respirators in a pandemic situation, through altered usage patterns and protocols. Fig. 2A presents the total consumption on a per N95 basis for a single provider using the assumptions previously stated. Considering the BAU scenario, the single provider would have used 9360 N95s, whereas that number is greatly reduced below to 78–156 under the different reuse and reprocessing scenarios. This is critical to consider, as American manufacturers are producing about 50 million N95 respirators each month, with a projected shortfall of 250 million respirators per month of those needed by healthcare workers (Hufford, 2020). A 2015 study centered around a potential 12 month influenza pandemic, found that depending on the level of infection, between 1.7 to 7.3 billion disposable respirators would be needed, and between 0.1 to 0.4 billion surgical masks for the infected patients to wear (Carias et al., 2015).

Cost is also a consideration in the usage of respiratory protection. Fig. 2B presents the cost to for the one physician we are modeling with respect to respiratory protection for the duration of the pandemic. The BAU scenario is projected to cost \$7020 over the 18 months, assuming that the cost of N95s stays at the pre-pandemic level of \$0.75 per respirator. If the cost were to increase up to \$6 per respirator (Reuters, 2020), that cost would rise to \$56,000, which is significant. Particularly as coping with the COVID-19 pandemic is straining the finances of many hospitals, which has caused furloughs for hospital staff and other cost saving measures (Neighmond, 2020; Paavola, 2020). The RAD scenario would cost around \$200 for the duration of the pandemic assuming normal pricing, and just over \$1000 if the prices were increased to \$6 per respirator. The reusable respirator monthly (RRCM) would cost \$156 over the course of the pandemic, assuming that it is not damaged during usage, while the weekly filter replacement scenario (RRCW) would cost \$576. This represents a significant potential for both cost savings and the ability to increase the quality of respiratory PPE which is provided during supply restriction over the typical usage scenario. However, it will not necessarily provide an economic benefit compared to the other N95 scenarios that include reuse, although this is function of the replacement frequency of the filters. A second economic

consideration with respect to the RRCM and RRCW scenarios would be the need to pre-purchase, fit test, and store these respirators, which would also come at a cost to the health care system.

The increased usage of respiratory protection during the current pandemic has the potential to increase the mass of waste which also must be dealt with. The usage of reusable elastomeric respirators and replacement cartridges which would potentially be stockpiled in preparation for the next pandemic, or the continuation of the current one, would reduce the quantity of waste generated by 98% (RRCM) and 93% (RRCW) compared to the BAU scenario. Which is significant, not only from a waste generation standpoint, but also in regards to the quantities of raw materials and energy of manufacturing which would be saved. This along with the need to not depend on the supply lines of single use items which must always be replenished presents an attractive opportunity. At the same time, all three conservation and reprocessing strategies for N95s also reduce the quantity of respirator waste compared to the BAU scenario: 99% (SPD), 99% (SPR), and 95% (RAD). This only, however, includes the masses of the N95s themselves, and not the resources needed and wastes generated by the reprocessing. The reprocessing options themselves, consume resources such as energy and chemicals, and have the potential to produce their own wastes. However, currently this information has not yet been quantified. With that said, the reprocessing which has been occurring during the COVID-19 pandemic is not seen as a long term measure, and only has been done due to shortages in supplies (Crotti, 2020). In the context of preparedness for pandemic respiratory protection, both elastomeric respirator scenarios offer waste generation savings over the BAU.

4. Discussion

Stockpiling reusable respirators to use during a pandemic situation is an opportunity to increase the resiliency of the medical system with respect to PPE. Based on the analysis performed in this work, it may also be economically favorable solution, particularly if price gouging occurs due to increased demand for respiratory protection. It would be the environmentally favorable solution with respect to masses of waste generated. Although many of the reuse and decontamination scenarios are less costly both economically and in terms of waste generation than the BAU scenario, it is well recognized that these are not practices that would be undertaken during non-pandemic situations (CDC, 2020c).

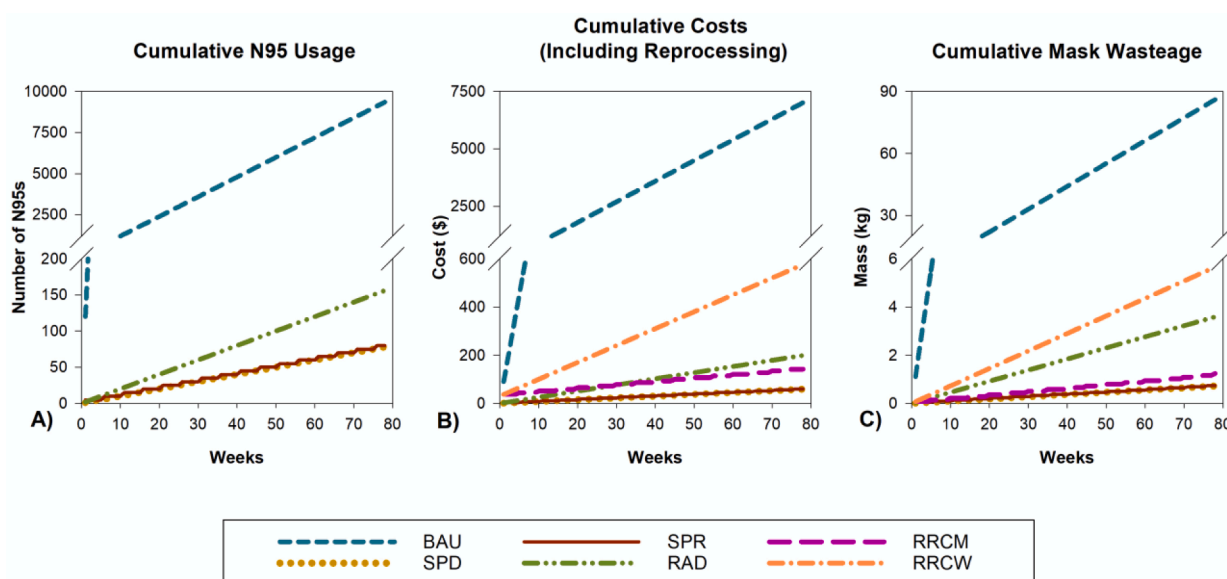


Fig. 2. Cumulative respiratory protection A) Number of single use N95 respirators, B) Cumulative costs of respiratory protection, C) Cumulative waste generated due to respiratory protection (BAU: Business as usual, SPD: Single Person Damage, SPR: Single Person Rotate, RAD: Reuse After Decontamination, RRCM: Reusable Respirator Cartridge Monthly, RRCW: Reusable Respirator Cartridge Weekly).

Medical supply chains are fragile even in the best of times. That has been shown previously, such as saline bag shortages that occurred after Hurricane Maria closed manufacturing in Puerto Rico (Mazer-Amirshahi and Fox, 2018). One buffering mechanism against the fragility is the National Strategic Stockpile, which was estimated to contain about 30 million surgical masks, 12 million N95s, and 5 million N95s that passed their expiration date (Elgin and Tozzi, 2020). As of early April 2020, 90% of the PPE in the National Strategic Stockpile had been distributed to states, with the remaining 10% held back for federal workers (Weixel, 2020). There have also been some suggested inequities with how the supplies were distributed. This has left states and hospital systems to compete with each other and the federal government for supplies, which also has the potential to drive up the cost of the supplies (Soergel, 2020).

Months into the current pandemic, there is still an inadequate supply of N95s for healthcare workers (Contrera, 2020). Major manufacturers have increased production of N95s, but are still unable to produce enough due to the rapid spread and intensification of the pandemic (Stankiewicz, 2020). A survey of US nurses between July and August 2020 found that 68% of nurses were required to reuse their N95s and 58% were required to reuse them for 5 days or more (Clark, 2020). There simply is not enough respiratory PPE for the current demand surge due to the pandemic. Stockpiling reusable respirators would be one approach to take for the next pandemic, and even introducing them now would increase the potential resiliency of this supply system.

4.1. The role of crowd sourced and manufactured PPE

In response to PPE shortages, hospitals, clinics and medical care facilities have extended a call asking for donations from community sourced and manufactured PPE substitutes. In the name of preparing a concerted effort, community groups have been formed. There are various examples of groups that have formed since the beginning of the pandemic, GetUsPPE, the Masked Warrior Project, Million Mask Challenge, Coronavirus Mask Makers, 100 Million Masks, Open Source Covid19 Medicals Supplies (OSMS), etc. (Lipner, 2020). Additionally, the #findthemasks mapping tool (Popkin, 2020) and Alexa's list (Collins, 2020) seek to inform donors of facilities requesting the PPE. The Get Us PPE group and OSMS are keeping tallies of PPE matches of facilities and donors. The OSMS group has developed a guide for those seeking to be donors. The purpose of these groups is to (1) not overwhelm facilities and workers with offers of help, (2) create cohesive guidelines for preparation of this substitute equipment and (3) connect the facilities asking for donations with donors in the area (OSMS, 2020). It is acknowledged that this approach is not ideal, but it has been recognized by multiple healthcare systems that it may become necessary to utilize these donations in the face of a shortage as evidenced by requests for donations on their behalf. Homemade surgical masks are not without concerns, such as sterility, construction, and appropriate use (Lipner, 2020). In terms of variety of masks prepared, there are 3D printed masks that resemble half face reusable PPE (Copper3D Inc., 2020), there is the conventional face mask made primarily of cotton materials, cloth covers prepared for existing conventionally manufactured PPE to better preserve these when in use, and face masks with a pocket to include a filter material. The filter material in the latter still needs replacement after use. Guidance for usage of homemade masks includes the use of a face shield that covers the entire front and sides of the face (CDC, 2020b). As a result of the homemade masks response, material scarcity has become an issue, including elastic, cotton fabric and filter insert materials. Substitute materials include repurposing old t-shirts and fabrics not intended for the filter materials. Other filter materials suitable for air purifying as machine components may not be suitable for mask applications due to the possibility of fiber shedding and consequent inhalation by the wearer (Hao et al., 2020). Additionally, the demand for mask materials has increased due to change in recommendations of mask wearing by the general public (CDC, 2020f).

Facing material shortages, one community group recommend one material, 100% spun bound nonwoven polypropylene which presents adequate breathability and impermeability and can be sourced from reusable grocery bags (Songer, 2020). Disinfection of this material is done by boiling for 10 min, because the melting point of this material is resistant to the boiling temperature of water. There is much debate with usage of other materials with respect to their breathability. Recent work has focused on testing the efficacy of different mask materials (Davies et al., 2013; Hao et al., 2020; Konda et al., 2020; Zhao et al., 2020).

There is a role for crowd sourced and manufactured PPE to play in the current COVID-19 pandemic, although ideally it would not be necessary. As the crisis continues to unfold, more insight will be generated as to its impact. One working theory is that requests for crowd sourced and manufactured PPE indicate a shortage at a particular hospital, while also simultaneously presenting an opportunity for increased resiliency of that hospital system. Particularly, if PPE is produced locally, and thus outside of the current bidding systems.

4.2. Summary points

Airborne transmission is a key route for spreading the COVID-19 pandemic. N95s are single use respirators which are not commonly utilized in medical settings, unless there is a risk of airborne transmission. Due to their typically infrequent usage, when the COVID-19 pandemic reached the US, there were insufficient stores and supplies of this protection. Earlier studies had suggested that in order to prepare for the next pandemic event, that stocks of reusable respirators should be created to increase the resiliency of respiratory protection (Institute of Medicine, 2006). However, as this was not done, use patterns for this PPE has shifted, in order to extend the lifetime of current supplies, including using different pathogen inactivation approaches. Although these pathogen inactivation approaches have been deemed permissible in a pandemic, they are not likely to be used during normal circumstances. When compared to the BAU scenario, these approaches have the potential to save money and generate less waste. However, if reusable respirators were stockpiled for an event such as a pandemic, they would also cost less economically and generate less waste than the BAU scenario, while likely providing better protection. This would increase the resiliency of the medical system, as new single use designed PPE would not need to be constantly sourced during a pandemic when demand is high, and used multiple times. Even if the cartridges for use in the stockpiled elastomeric respirators were to expire, there is experimental evidence that they would still be suitable for usage during a pandemic situation (Patolia et al., 2020).

4.3. Limitations

Limitations exist for this literature review with the limited analysis included to assist in highlighting the information, as they do for all work. The first is due to data that is currently not available, this includes the costs of reprocessing the N95s both internally and externally. The processes being deployed right now were not commonly utilized prior to the current pandemic, and thus quite a bit of information is either currently unknown or has not been made available to researchers. Beyond that, information currently does not exist as to the field tested longevity of the reprocessed N95s. Second, the scenarios included for illustrative purposes of the literature review, but there are many different types of medical personnel who utilize PPE. The example of a physician was chosen as an example to assist in illustrating this information. It would be interesting to extend the current work to include all of the medical and nonmedical personnel in a clinic or hospital setting to model their PPE consumption over a period of time. Third, limited samples of PPE were utilized to produce the mass data, due to current conservation efforts. Ideally, a greater variety of brands and samples would be utilized in the data collection.

5.0. Conclusions

Adequate PPE for health care workers is critical in the current COVID-19 pandemic. Unfortunately, due to multiple issues there is a current shortage for medical staff, which has resulted in PPE being utilized in manners that do not typically occur during non-crisis situations. The current reliance on single use respiratory PPE (i.e. N95s) is an issue which decreases the resiliency of the system overall. The use of reusable respiratory protection has the potential to reduce the economic cost of PPE under supply restriction, both when price gouging occurs and on circumstances where there are spikes in consumption. In particular, the current pandemic is anticipated to last more than just a few months, meaning that there is a sustained requirement for PPE, which has the potential to be partially mitigated through the usage of reusable respiratory PPE.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2020.105262](https://doi.org/10.1016/j.resconrec.2020.105262).

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